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Penetration of Multiple, Axially Offset, Disk-Shaped Penetrators

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Penetration of Multiple, Axially Offset, Disk-Shaped Penetrators

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Abstract

The terminal ballistic performance of high-velocity, low length-to-diameter (L/D) ratio projectiles impacting steel targets has been a topic of considerable interest in penetration mechanics to evaluate the efficacy of segmented projectiles. A computational study has been conducted to examine the penetration performance of multiple (i.e., three), axially offset, disk-shaped projectiles impacting semi-infinite rolled homogeneous armor (RHA). A constant 3.25 projectile diameter separation distance between each disk-shaped projectile was maintained for the impact conditions modeled in this study. The three-dimensional (3-D) simulations suggest that the total depth of penetration into steel is not degraded for disk offsets less than 0.5 projectile diameters based on the range of disk offsets modeled in the study.

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1. Introduction

The penetration performance of high-density, low length-to-diameter (L/D) ratio projectiles impacting steel targets has been a topic of considerable interest in penetration mechanics due to the speculated performance of a segmented rod projectile. This has been spurred by the observation that normalized penetration performance, i.e., penetration per unit length (P/L), increases as L/D decreases, provided that the impact velocity is relatively high. Computational and experimental research to date has focused on penetrators shaped as either spheres or right-circular cylinders, with an L/D of 1 or slightly greater [1–18]. De Rosset and Sherrick [19] modeled segmented rod performance at ordnance velocity for high-density tungsten alloy segments with an L/D of 1. They observed that multiple segment rod performance was less than that predicted by simply multiplying single segment performance by the total number of segments due to interactions with residual segment material in the penetration cavity.

Recently, computational and experimental studies have focused on characterizing and understanding the penetration mechanics of high-density metallic projectiles with an L/D ratio of less than 1 [20–22]. Herbette [23] noted a dramatic increase in P/L for steel disks with an L/D ratio of 1/30, impacting aluminum targets at 2 km/s when compared to penetrators with considerably greater L/D. Orphal and Franzen [24] also reported a significant increase in P/L as projectile L/D was reduced from 1 to 1/8 for tungsten, tungsten alloy, and tantalum alloy projectiles impacting steel targets at striking velocities between 1.5 km/s and 7.5 km/s. A thorough review of the fundamentals of penetration and perforation of solids and their application to practical problems has been prepared by Goldsmith [25], Johnson [26], Backman and Goldsmith [27], Zukas et al. [28], and Zukas [29].

This report summarizes a numerical study to examine the penetration performance of multiple (i.e., three) tungsten heavy alloy (WHA), axially offset, disk-shaped projectiles impacting semi-infinite rolled homogeneous armor (RHA) at a striking velocity of 2.6 km/s. The separation distance between each disk-shaped projectile is 3.25 projectile diameters. Segment offsets between 0 and 1 projectile diameters were modeled in the study. The impact dynamics of multiple, axially offset, disk-shaped projectiles impacting a steel target are discussed in the sections that follow.

2. Numerical Model

The numerical study was conducted with the Eulerian wave propagation code CTH [30]. A single program multiple data (SPMD) paradigm with explicit message passing between computational subdomains was used to map the global computational domain onto a scalable architecture [31]. CTH is a family of computer programs for modeling solid dynamics problems involving shock wave propagation, multiple materials, and large deformations in one, two, and three dimensions. CTH employs a two-step solution scheme: a Lagrangian step followed by a remap step. The conservation equations are replaced by explicit finite volume equations that are solved in the Lagrangian step. The remap step uses operating splitting techniques to replace multidimensional equations with a set of one-dimensional (1-D) equations. The remap or advection step is based on a second order accurate van Leer scheme. To minimize material dispersion, a high-resolution material interface tracker is available. Both analytical and tabular equations of state are available to model the hydrodynamic behavior of materials. Models for elastic-plastic behavior and high-explosive detonation are also available.

The CTH simulations reported herein used a linear-Hugoniot shock-particle velocity equation of state to model the hydrodynamic behavior of the materials. An elastic perfectly plastic material model was used for WHA and RHA, with dynamic yield strengths of 19.3 kilobar (kbar) and 7.0 kbar, respectively [20]. The simulations used a three-dimensional (3-D) Cartesian coordinate system. The multiple material temperatures and pressures thermodynamic model was used to calculate separate temperatures and pressures for materials in multimaterial cells. The Sandia Modified Young's Reconstruction Algorithm (SMYRA) [32] was used to track material interfaces and minimize material dispersion in multimaterial cells. The March 1999 release of the CTH code was used to conduct the simulations discussed in this report. The computational mesh is composed of 0.4-mm cubic cells in the disk-target interaction region, with a geometric cell expansion to extend the mesh to the boundaries of the computational domain. The mesh is composed of a total of 6,346,800 cells. The 0.4-mm cubic cell subgrid region spanned from –6.4 to 2.4 cm in the X-coordinate direction, 0.0 to 3.2 cm in the Y-coordinate direction, and –3.2 to 2.04 cm in the Z-coordinate direction. The X-Z plane is modeled as a symmetry boundary to minimize the size of the computational mesh. To further reduce the number of required computational cells, the CTH data initialization and modification (DIATOM) input set was used to insert the second and third disk-shaped penetrators into the simulation at user-specified times, 17.692 μs and 35.385 μs, respectively, to accurately model the separation distance between

individual disk-shaped penetrators. The DIATOM input set permits time-dependent insertion of material during the course of a calculation, i.e., virtual objects.

The geometry of each disk-shaped penetrator is constant, with a diameter of 16 mm and a thickness of 2 mm. The L/D of each disk is 1/8. Each disk-shaped penetrator was assigned an initial impact velocity of 2.6 km/s in the negative Z-coordinate direction. The separation distance between individual disks is 3.25 projectile diameters. This separation distance is sufficient to allow each disk to complete its contribution to the overall penetration before the next disk impacts the target. The target was modeled as a semi-infinite block of RHA. Figure 1 shows a schematic of the impact conditions examined in this study.

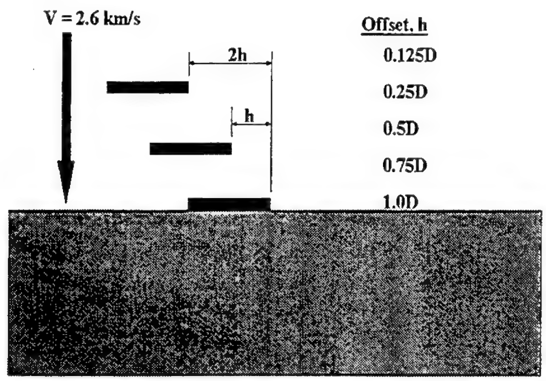

Figure 1. Multiple, axially offset, disk-shaped penetrator impact geometry.

3. Penetration of Single and Axially Aligned, Multiple Disks

Baseline simulations were conducted to assess the overall influence of axial offset on the penetration of multiple, disk-shaped penetrators. The first baseline simulation modeled the impact of a single disk-shaped penetrator. The single disk-shaped penetrator geometry was identical to the individual disk geometries modeled in the offset simulations, i.e., L/D = 1/8, and D = 16 mm. The single disk impact was modeled using the same 3-D computational domain and mesh resolution as established for the offset simulations. In addition, the same target and penetrator material properties were defined for the single disk impact simulation. The calculation was run for a simulated time of 50 μs. The predicted penetration channel for the single disk impact is shown in Figure 2.

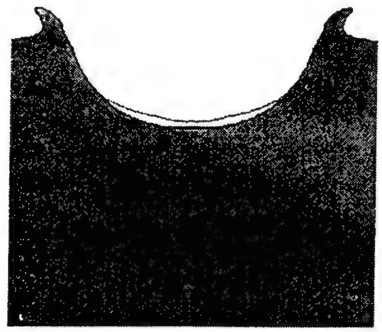

Figure 2. Penetration of 2.6-km/s single disk impact into semi-infinite RHA, at 50 μs.

Figure 3 shows the time history for two Lagrangian tracer particles initially located along the centerline of the disk, with Tracer 1 positioned on the impact face of the disk and Tracer 2 positioned on the rear surface of the disk. The predicted final depth of penetration at 50 μs is 10.8 mm or a predicted normalized penetration, P/L, ratio of 5.4. Figure 3 indicates that the single disk impact achieves a maximum penetration of 11.2 mm at about 25 μs.

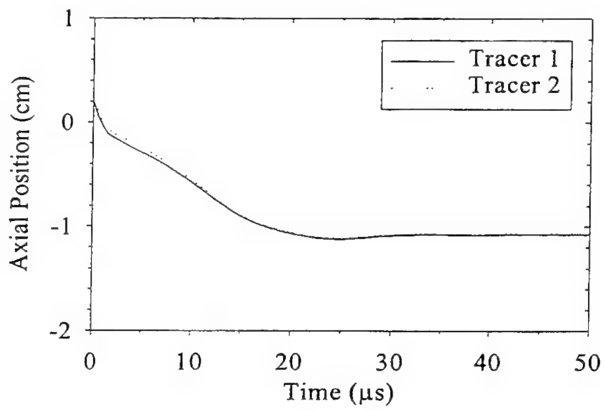

Figure 3. Tracer position history for single disk impact.

Figure 4 shows the axial velocity histories for tracer particles positioned on the front and rear surfaces of the disk. The axial velocity initially reaches 0 at about 25 μs, followed by a short duration of rebound until all of the impact kinetic energy has been absorbed. This suggests that for a multiple disk impact event, the second disk should be staged to impact the target at about 20–25 μs after the first disk impact in order to augment the axial momentum imparted to the target by the first disk. This corresponds to a disk-separation-to-projectile-diameter, S/D, ratio of 3.25–4.1 projectile diameters. Note that the time for an individual disk to traverse a separation distance of 5.2 cm is 20 μs. At 20 μs, the single disk

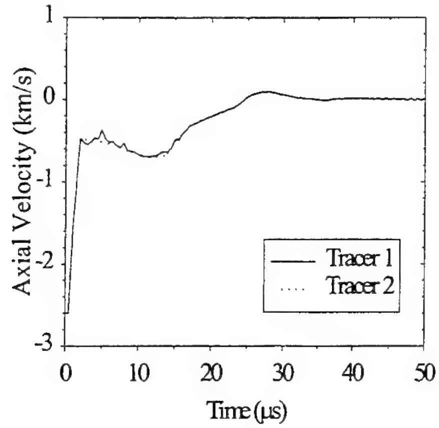

Figure 4. Tracer velocity history for single disk impact.

penetration is 10.7 mm, which corresponds to 95.5% of the predicted maximum depth of penetration and 99.1% of the predicted final depth of penetration. As a result, a normalized separation distance, S/D, of 3.25 projectile diameters was selected for the multiple disk impact simulations.

A second baseline simulation modeled perfectly aligned (no offset), multiple disk-shaped penetrators impacting a semi-infinite RHA target at 2.6 km/s. Figure 5 shows the predicted penetration channel at 100 μs. The penetration channel exhibits a scalloped penetration channel that corresponds to the impact of each disk-shaped penetrator. Some debris ejecta are noted along the centerline. Figure 6 shows the time history of a Lagrangian tracer particle initially located on the centerline, 0.2 mm below the target-impact face. The impact of each disk-shaped penetrator is clearly evident in Figure 6. The second disk impact occurs at about 25 μs, and the third disk impact occurs at about 50 μs.

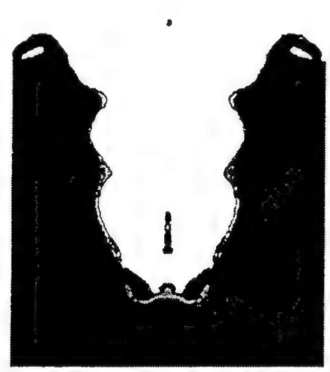

Figure 5. Penetration of perfectly aligned, multiple disk impact at 2.6 km/s.

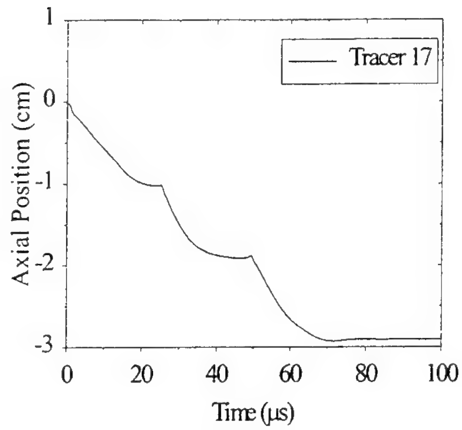

Figure 6. Tracer position history for perfectly aligned, multiple disk impact.

The second disk impacts the target after the first disk has penetrated 10.2 mm into the target or approximately 94% of the predicted final depth of penetration for the baseline single disk impact previously discussed. Impact of the second disk increases the depth of penetration to 19.1 mm. At 48.5 μs, the third disk impacts the target, which contributes an additional 10 mm of penetration, resulting in a final predicted depth of penetration, along the centerline, of 29.1 mm. Material plots at intermediate times for this multiple disk impact event indicate that the third disk interacts with debris ejecta, generated during the second disk impact, along the centerline prior to impacting the target. The penetration channel produced as a result of this interaction is slightly deeper (29.8 mm) at the channel side wall when compared to depth of penetration (29.1 mm) at the centerline (see Figure 5). In addition, the interaction of the second and third disks, with residual penetrator material at the bottom of the channel, results in a predicted depth of penetration that is less than that suggested by simple multiplication of the baseline single disk penetration (10.8 mm) by a factor of 3.

4. Penetration of Axially Offset Disks

A set of 3-D CTH simulations was conducted to examine the penetration performance of multiple, axially offset, disk-shaped penetrators striking semi-infinite RHA targets. The study examined axial offsets between 0 (perfect alignment) and 1 projectile diameter. Each disk-shaped penetrator had an impact kinetic energy of 23.6 kJ, yielding a total impact energy of 70.8 kJ. The predicted maximum depth of penetration for each offset studied is presented in

Table 1. Figure 7 shows the predicted penetration channels at 100 μs for axial offsets of 0.25D, 0.5D, 0.75D, and 1.0D. All of the penetration channels are asymmetric. Distinct penetration channels for each disk impact are observed in the penetration channels, with axial offsets of 0.75D, and 1.0D. Review of the penetration channel for offsets of 0.5D and below, shown in Figure 7, as well as intermediate material plots during the development of the penetration channel, exhibits interactions between the side walls of the penetration channel and the trailing offset disks. This side wall interaction deflects each trailing disk towards the centerline of the penetration channel produced by the impact of the first disk. For axial offsets less than 0.5D, more of the impact energy is absorbed in producing a deeper penetration channel rather than increasing the diameter of the penetration channel.

Table 1. Penetration of multiple, axially offset, disk-shaped penetrators.

Simulation	Axial Offset (mm)	Penetration (mm)
Off 0	0	29.8
Off_125	2	32.0
Off_25	4	32.4
Off_5	8	33.2
Off_75	12	23.5
Off_1	16	22.0

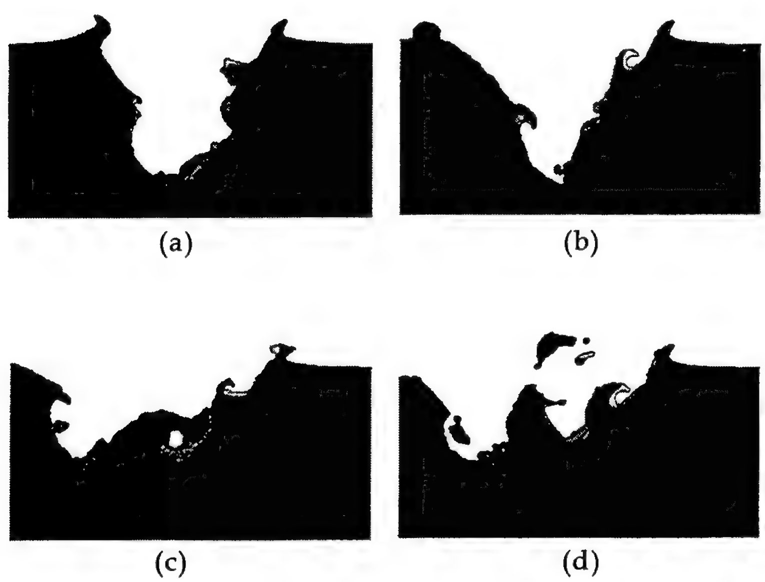

Figure 7. Penetration channels for axial offsets (a) 0.25D, (b) 0.5D, (c) 0.75D, and (d) 1.0D.

The larger axial offsets (0.75D and greater) produce discrete penetration channels for each disk impact. At these offsets, there is no coupling of the impact energy to increase the depth of penetration. Effectively, a large portion of the impact energy is absorbed in producing a larger diameter penetration channel. Comparison of the predicted depth of penetration of axial offsets of 0.5D and 0.75D (see Table 1) shows a 9.7 mm (29%) decrease in depth of penetration. Thus, axial offsets larger than 0.5D will significantly decrease penetration performance. This decrease in penetration performance can be seen in Figure 8, which summarizes the normalized depth of penetration as a function of axial offset.

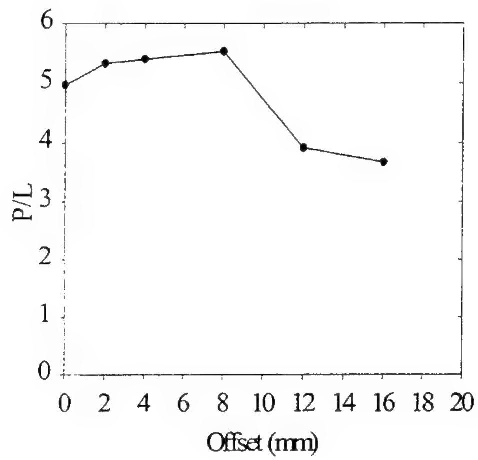

Figure 8. Penetration of multiple, axially offset, disk-shaped penetrators into RHA at 2.6 km/s.

5. Conclusion

The terminal ballistic performance of multiple, axially offset, high-velocity, low L/D ratio projectiles impacting semi-infinite RHA has been studied using 3-D continuum mechanics simulations. This numerical study investigated axial offsets between 0 (perfect alignment) and 1 projectile diameter. The impact scenarios modeled in this study suggest that the depth of penetration into steel is not degraded for axial offsets less than 0.5 projectile diameters. For the zero offset case, it was observed that as a result of interactions between the trailing disks and residual penetrator material at the bottom of the penetration channel, the predicted depth of penetration is less than that suggested by simple multiplication of the baseline single disk penetration by the number of disks impacting the target.

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The terminal ballistic performance of high-velocity, low length-to-diameter (L/D) ratio projectiles impacting steel targets has been a topic of considerable interest in penetration mechanics to evaluate the efficacy of segmented projectiles. A computational study has been conducted to examine the penetration performance of multiple (i.e., three), axially offset, disk-shaped projectiles impacting semi-infinite rolled homogeneous armor (RHA). A constant 3.25 projectile diameter separation distance between each disk-shaped projectile was maintained for the impact conditions modeled in this study. The three-dimensional (3-D) simulations suggest that the total depth of penetration into steel is not degraded for disk offsets less than 0.5 projectile diameters based on the range of disk offsets modeled in the study.

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